HORIZONTAL DIFFUSION COMPUTATIONS IN THE CYCLE 45 OF ARPEGE/IFS.

YESSAD K. (METEO-FRANCE/CNRM/GMAP/ALGO)

June 28, 2017

Abstract:
This documentation recalls some basics about horizontal diffusion schemes, and describes how they are implemented in ARPEGE/IFS and its LAM (limited area model) counterpart. The ECMWF way of implementing them (which is slightly different from the METEO-FRANCE one) is not described in detail. There is a main horizontal diffusion scheme, a sponge and a Rayleigh friction. An organigramme is provided.

Résumé:
Cette documentation rappelle quelques notions sur les schémas de diffusion horizontale, et décrit comment ces schémas sont utilisés et codés dans ARPEGE/IFS et sa version à domaine limité. La version de ces codes utilisée au CEP n’est pas décrite en détail, dans la mesure où elle diffère un peu de ce qui est utilisé à METEO-FRANCE. Il y a un schéma principal de diffusion horizontale, une éponge et une friction de Rayleigh.
Contents

1 Introduction. 3

2 Formulation of the horizontal diffusion schemes. 4
   2.1 Main horizontal diffusion scheme. 4
   2.2 Sponge. 5
   2.3 Rayleigh friction. 5
   2.4 Filtering pressure gradient term. 5
   2.5 Nudging. 5

3 Discretisation of the horizontal diffusion schemes. 6
   3.1 Main horizontal diffusion scheme. 6
      3.1.1 Main horizontal diffusion scheme in unstretched ARPEGE/IFS. 6
      3.1.2 Main horizontal diffusion scheme in LAM model. 7
      3.1.3 Main horizontal diffusion scheme in stretched ARPEGE/IFS. 8
   3.2 Modification of the horizontal diffusion scheme if “SLHD” interpolations are done in the semi-
      Lagrangian scheme. 9
   3.3 Application of diffusion to each variable. 9
      3.3.1 Application to GMV variables and to GFL variables in 3D models. 9
      3.3.2 Application to temperature. 10
      3.3.3 Application to GMV variables in 2D models. 10
   3.4 Other diffusive processes schemes. 10
      3.4.1 Sponge. 10
      3.4.2 Rayleigh friction. 11
      3.4.3 Filtering pressure gradient term. 11

4 Organigramme of the horizontal diffusion computations. 12
   4.1 Order of spectral computations. 12
   4.2 Set-up and control routines until STEPO. 12
   4.3 Direct code under STEPO or tangent linear code under STEPOTL for spectral calculations. 13
   4.4 Adjoint code under STEPPOAD for spectral calculations. 13
   4.5 Rayleigh friction done in grid-point space. 13
   4.6 Action done by set-up routines. 14
   4.7 Control routines. 14
   4.8 Action done by routines under STEPO, STEPOAD or STEPOTL. 14

5 Some distributed memory features in spectral space. 15

6 Module and namelist variables. 16

7 References. 18
   7.1 Publications: 18
   7.2 Internal notes: 18
1 Introduction.

* General considerations for ARPEGE/IFS (global model): Horizontal diffusion computations are generally spectral computations. There is a main horizontal diffusion scheme in spectral space. In case of constant resolution, the main horizontal diffusion scheme is discretised by a purely diagonal operator in spectral space. The main horizontal diffusion scheme is implicit in order to remain stable even with high diffusion coefficients and are called after the semi-implicit scheme. Horizontal diffusion is called after inversion of the semi-implicit scheme and before nudging.

* Horizontal diffusion in LAM model: Horizontal diffusion computations are still spectral computations. There is a main horizontal diffusion scheme only. For the main horizontal diffusion scheme, the formulation looks like the unstretched global model one. There are specific routines for spectral calculations.

* Sponge: An additional sponge may be done near the top of the model. This sponge is done in spectral space for spectral variables and in grid-point space for purely grid-point variables.

* Rayleigh friction: There is a Rayleigh friction in the grid-point space computations which acts only in upper atmosphere for the $U$-component (and optionally for the $V$-component) of the horizontal wind.

* Pressure gradient term filtering: A specific filter has been implemented to filter pressure gradient term in spectral space. This filter is currently available for unstretched un-tilted global models and LAM models.

* Two-time level semi-Lagrangian scheme: equations are written for a leap-frog scheme. The algorithm remains the same for a two-time level semi-Lagrangian scheme.

* Deep layer equations: For convenience, equations are written with the geographical horizontal gradient operator $\nabla$, which is used in the horizontal diffusion scheme for thin layer equations. For deep layer equations, the operator actually used is $[\frac{r}{r} \nabla]$, where $r$ is the actual radius, to simulate a “pseudo-geographical” diffusion, instead of $\nabla$: this approximation is reasonable and allows to avoid any tricky modification in the horizontal diffusion spectral computations; use of the true geographical gradient $\nabla$ sticks to the grid-point calculations.
2 Formulation of the horizontal diffusion schemes.

2.1 Main horizontal diffusion scheme.

* General formulation: The main horizontal diffusion formulation is close to:

\[
\left( \frac{\partial X}{\partial t} \right)_{\text{hd}} = -K_X M \nabla^r X
\]

where \( K_X \) is a vertically dependent and horizontally constant coefficient. \( K_X \) is generally complex: \( \exp(0.5\pi ir) \) multiplied by a real positive coefficient. \( r \) is the power of the horizontal diffusion scheme. \( M \) is the mapping factor.

In global model:

\[
K_X = \exp(-0.5\pi ir) \left[ \frac{N_s(N_s + 1)}{a^2} \right]^{-r} \Omega h_X g
\]

\( a \) is the mean Earth radius, \( N_s \) is a function of the Earth rotation \( (0.00007292115 \, \text{s}^{-1}) \). \( h_X \) is a constant coefficient for each prognostic variable. There are seven constants, one for vorticity \( (h_{\zeta}) \), one for divergence \( (h_D) \), one for temperature \( (h_T) \), one for humidity \( (h_q) \), one for ozone \( (h_{CO3}) \), one for the extra GFL variables \( (h_{EXT}) \), one for the surface hydrostatic pressure \( (h_{SP}) \) which is also used for the equivalent height in the 2D model. There are additional constants for non-hydrostatic variables in the non-hydrostatic model. For divergence expression of \( h_D \) matches:

\[
1 \Omega^{-1} h_D = \frac{2\pi}{N_{\text{lon}}} \frac{r_{\text{dampdiv}}}{r_{\text{dxtau}}} \left( 1 + 0.5 r_{\text{nlginc}} \right)^{2.5}
\]

\( r_{\text{nlginc}} \) is a tuning parameter; \( N_{\text{lon}} \) is the number of grid-points on a latitude located near the equator of the computational sphere.

In LAM model:

\[
1 \Omega^{-1} h_D = \frac{\sqrt{L_x^2 + L_y^2}}{N_a} \left( 1 + 0.5 r_{\text{nlginc}} \right)^{2.5} \Omega h_X g
\]

\( a \) is the mean Earth radius, \( L_x \) and \( L_y \) are respectively the zonal and meridian lengths of the domain, these lengths being taken on a surface located at a distance \( a \) from the Earth centre, \( N_a \) is the zonal truncation, \( N_s \) is the meridian truncation.

\[
\frac{1}{\Omega_h D} = \frac{[\Delta X]_{\text{gp}}}{r_{\text{dxtau}}} \frac{\left( 1 + 0.5 r_{\text{nlginc}} \right)^{2.5}}{r_{\text{dampdiv}}}
\]

where:

\[
[\Delta X]_{\text{gp}} = \sqrt{0.5 \left( [\Delta X]_{\text{gp,zonal}}^2 + [\Delta X]_{\text{gp,merid}}^2 \right)}
\]

\([\Delta X]_{\text{gp,zonal}}\) and \([\Delta X]_{\text{gp,merid}}\) are respectively the zonal and meridian grid-point mesh-sizes taken at a location where the mapping factor is equal to 1.

In both global and LAM models, for the other 3D upper air fields:

\[
\frac{1}{\Omega h_X} = \frac{r_{\text{dampdiv}}}{r_{\text{dampdiv}}} \frac{1}{\Omega h_D}
\]

which can be rewritten:

\[
(\Omega h_X) = \frac{r_{\text{dampdiv}}}{r_{\text{dampdiv}}} (\Omega h_D)
\]

* Modifications brought to this scheme if the SLHD (semi-Lagrangian horizontal diffusion) interpolations are done in the semi-Lagrangian scheme: When the advection scheme is a semi-Lagrangian one, it is possible to activate more diffusive interpolations in the semi-Lagrangian scheme ("SLHD" diffusion), and in this case the horizontal diffusion scheme must be modified:

- Less diffusion in the above formulation (generally by reducing the value of function \( g(l) \)).

- Adding of a second horizontal diffusion scheme for divergence and vorticity (and also vertical divergence in the NH model): this scheme has the same formulation as the previous one, but the following variables are changed:

  - \( h_X \) becomes \( h_{\text{hd}X} \) (currently \( \frac{1}{\Omega h_{\text{hd}X}} = \frac{1}{r_{\text{dampdiv}}} \Omega h_X \)), i.e. \( (\Omega h_{\text{hd}X}) = (r_{\text{dampdiv}}(\Omega h_X)) \).
- $K_X$ becomes $K_{hd}X$.
- the power $r$ becomes $s$ ($s$ is generally above $r$).
- vertical profile $g$ becomes $g_{hd}$.

The “SLHD” diffusion can now be activated on a subset of prognostic variables and the above modifications are applied only to this subset of variables.

* Additional remarks: In the unstretched version of global model, $M = 1$. In LAM model, the horizontal variations of $M$ are generally neglected and $M$ is replaced by a constant hidden in the coefficients $K_X$ and $K_{hd}X$. So diffusion looks like the unstretched global model one.

### 2.2 Sponge.

The sponge is a sort of horizontal diffusion applied near the top of the model; formulation is close to:

$$\left(\frac{\partial X}{\partial t}\right)_{hd} = -K_{spng X}(X - X_{moy})$$ (8)

where $K_X$ is a vertically dependent and horizontally constant coefficient. $X_{moy}$ is the horizontal average of $X$ on the forecast domain.

### 2.3 Rayleigh friction.

The following scheme is applied on the $U$-component of the momentum equation.

$$\left(\frac{\partial U}{\partial t}\right)_{fric} = -K_{fric}U$$ (9)

$-K_{fric}U$ is a Rayleigh friction which is activated if $LRFRIC=T.$ in NAMdyn. $K_{fric}$ is a vertical dependent coefficient which is non-zero only for a standard pressure lower than a threshold stored in variable $YRDYN%RRFPLM$.

This Rayleigh friction can be optionally applied on the $V$-component of the momentum equation.

$$\left(\frac{\partial V}{\partial t}\right)_{fric} = -K_{fric}V$$ (10)

### 2.4 Filtering pressure gradient term.

This filtering is activated in spectral space when $LGRADSP=T.$. It is applied to vorticity component of pressure gradient term. Divergent component is kept unfiltered. In NH LAM models pressure departure is filtered too.

### 2.5 Nudging.

This scheme called after horizontal diffusion is a linear relaxation of prognostic variables towards pre-defined fields and is not properly saying a diffusion scheme, so it will not be described in detail in this documentation. Pre-defined fields (for example climatological fields) can be read on a file. Nudging coefficients can be different for each variable. Nudging coefficients are not vertically dependent, except for the upper atmosphere where they can be set to zero. Nudging is applied to all variables present in spectral space. There is also nudging for grid-point variables in grid-point space, such surface temperature, surface moisture, deep moisture and snow depth. Nudging is controlled by $LNUDG$ in namelist NAMNUD.
3 Discretisation of the horizontal diffusion schemes.
3.1 Main horizontal diffusion scheme.
3.1.1 Main horizontal diffusion scheme in unstretched ARPEGE/IFS.

* Discretisation: Calculations are done in spectral space. The discretised equation which is coded is:
\[
X_{(m,n)}^{+} - X_{(m,n)}^{-} = -\Omega h X g(l) f(n, N, n_0(X), x_0, r)Dt X_{(m,n)}^{-}
\]
(11)
where the superscripts + and − indicate respectively variables after horizontal diffusion and variables before horizontal diffusion, Dt is the time step in the first integration step and twice the time step later (leap frog scheme), n is the total wave number (between 0 and the truncation \(N_s\)), \(m\) is the zonal wave number (between \(-n\) and \(n\) in a triangular truncation), \(r\) is the order of the horizontal diffusion operator, \(N\) is a reference wave number, \(n_0(X)\) is a threshold depending on variable \(X\) (generally zero except for vorticity where it is 2 at METEO-FRANCE and 0 at ECMWF), \(x_0\) is a threshold between 0 and 1. \(\nabla^r\) is the first order horizontal reduced derivative operator (i.e in the grid point space, \(\nabla = M\nabla^r\)), where \(M\) is the mapping factor. This horizontal diffusion scheme is an implicit horizontal diffusion scheme (in the right-hand side member of the equation there is \(X_{(m,n)}^{+}\) and not \(X_{(m,n)}^{-}\)). Equation (11) becomes (12):
\[
X_{(m,n)}^{+} = \frac{1}{1 + K_X(n)Dt} X_{(m,n)}^{-}
\]
(12)
where:
\[
K_X(n) = \Omega h X g(l) f(n, N, n_0(X), x_0, r)
\]
(13)
In 2D models (shallow-water model for example), \(g(l)\) is replaced by 1 and \(N\) is always equal to \(N_s\).

* Horizontal dependency for applications at METEO-FRANCE: Expression of \(f(n, N, n_0(X), x_0, r)\) is currently:
\[
f(n, N, n_0(X), x_0, r) = \max \left(0, 1 - \frac{\frac{\max(0, n_0(N(n+1))-n_0)}{\max(0, N(N(n+1)-n_0))} - x_0}{1 - x_0}\right)^r
\]
(14)
An exact discretisation of equation (1) would give:
\[
f(n, N, n_0(X), x_0, r) = f(n, N_s, 0, 0, r)
\]
(15)
One can notice that this discretisation is equivalent to apply a purely diagonal operator in spectral space. 
\(N\) can be vertically constant (taken equal to the truncation \(N_s\)) or vertically variable (varies between \(N_s\) near the ground and \(N_2\) near the top, with \(N_2 < N_s\)).

* Horizontal dependency for applications at ECMWF: Function \(f\) has a more tricky shape which is not detailed there.

* Vertical dependency of \(g\): \(g(l)\) only depends on the altitude, and several profiles have been coded, according to the value of namelist variable YRDRYN%PROFILEHD.

The operational version of ARPEGE (case YRDRYN%PROFILEHD=3) uses the following profile: for the layer number \(l\), expression of \(g(l)\) is:
\[
g(l) = \min \left(\frac{y_0}{\Pi_{at}(l)} 1 - \frac{y_0}{\Pi_{at}(l)} y_5\right)
\]
(16)
where \(\Pi_{at}(l)\) is the standard atmosphere pressure for the layer number \(l\), \(\Pi_{ref}\) is a reference pressure (sea level pressure for the standard atmosphere: 1013.25 hPa). \(y_0\) is between 0 and 1: \(g(l) = 1\) if \(\Pi_{at}(l)/\Pi_{ref}\) is above \(y_0\) and \(g(l)\) is above 1 if \(\Pi_{at}(l)/\Pi_{ref}\) is below \(y_0\). \(y_5\) is between 0 and \(y_0\), in practical it is significantly lower than \(y_0\) and it is used to avoid too much diffusion in the high stratosphere and in the mesosphere.

A more flexible profile has been implemented (YRDRYN%PROFILEHD=2) in order to increase \(g\) in the stratosphere. Two additional reference pressures \(\Pi_{tp}\) and \(\Pi_{at}\) are defined (\(\Pi_{tp} < \Pi_{at}\)).

- For \(\Pi_{at}(l) > \Pi_{at}\), \(g(l)\) is defined by formula (16).
- For \(\Pi_{at}(l) < \Pi_{tp}\), \(g(l)\) is set to a maximum value \(g_{max}\) provided by namelist.
• For $\Pi_{nst}(l)$ between $\Pi_{ls}$ and $\Pi_{tr}$, $g(l)$ writes:

$$g(l) = \frac{g_a(\Pi_{nst}(l)/\Pi_{ls})^q + g_b}{1 + (\Pi_{nst}(l)/\Pi_{ls})^q}$$

$g_a$ and $g_b$ are two constants computed in order that function $g(l)$ is continue for $\Pi_{nst} = \Pi_{ls}$ and $\Pi_{nst} = \Pi_{tr}$.

$q$ is an exponent ($q > 0$) allowing an additional freedom degree for vertical variations of $g$.

An alternate (ECMWF-type profile) is also coded ($YRDYN\%NPROFILEHD=1$). Several formulae are coded according to the top of the model, leading to $g(l)$ functions varying between 1 at the surface and 16 at the top.

* Vertical dependency of $N$: The ARPEGE operational suite generally uses the constant profile $N = N_s$. Climatic applications may require a stronger diffusion in the stratosphere; this is possible via a variable profile $N(l)$ depending on the standard pressure. A reference truncation $N_2$ is defined for the high stratosphere, and two pressures thresholds $\Pi_1$ and $\Pi_2$ are defined via variables $y_1$ and $y_2$ ($y_1 > y_2$ and are both between 0 and 1).

$$\Pi_1 = \Pi_{ref} \times y_1$$

$$\Pi_2 = \Pi_{ref} \times y_2$$

Definition of $N(l)$ is:

- For $\Pi_{nst} > \Pi_1$, $N(l)$ is equal to $N_s$.
- For $\Pi_{nst} < \Pi_2$, $N(l)$ is equal to $N_2$.
- For $\Pi_{nst}$ between $\Pi_1$ and $\Pi_2$, $N(l)$ writes:

$$N(l) = \text{nint} \left[ \left( \frac{\Pi_1}{\Pi_{nst}} \right)^{\Pi_{nst} - \Pi_2} N_s^r + \left( \frac{\Pi_2}{\Pi_{nst}} \right)^{\Pi_{nst} - \Pi_1} N_2^r \right]^{1/r}$$

This vertical profile is available for all values of $YRDYN\%NPROFILEHD = 1$ to 3. An old code (put under $YRDYN\%NPROFILEHD=4$) is still present to take account of $\Pi_2$ and $N_2$ but this piece of code difficult to read and maintain is expected to disappear in the future. Users must switch on $YRDYN\%NPROFILEHD=3$.

3.1.2 Main horizontal diffusion scheme in LAM model.

* Discretisation: Compared to global model, the main differences are:

- $K_X$ also depends on the zonal wavenumber $m$.
- Function $f$ also depends on $m$ and on the zonal truncation $N_{ms}$, and has a different expression.
- $n_0$ is replaced by zero in the code (for convenience one will let $n_0$ in the following formulae).
- Equation (11) becomes:

$$X_{(m,n)}^+ - X_{(m,n)}^- = -\Omega h_x \frac{g(l)f(m,n,N,n_0(X),x_0,r)DtX_{(m,n)}^-}{N_m + h_x}$$

(17)

where $N_m$ is a reference zonal wavenumber.

- Equation (12) becomes:

$$X_{(m,n)}^+ = \frac{1}{1 + K_X(m,n)Dt} X_{(m,n)}^-$$

(18)

- Equation (13) becomes:

$$K_X(m,n) = \Omega h_x \frac{g(l)f(m,n,N,n_0(X),x_0,r)}{N_m + h_x}$$

(19)

* Horizontal dependency for applications at METEO-FRANCE: Expression of $f(m,n,N,n_0(X),x_0,r)$ is currently:

$$f(m,n,N,n_0(X),x_0,r) = \max \left( 0, \left( \frac{x_0^r + N_m^r}{N_m^r} - x_0 \right) \right)$$

(20)

An exact discretisation of equation (1) would give:

$$f(m,n,N,n_0(X),x_0,r) = f(m,n,N_{int},N_0,0,0,r)$$

(21)

* Vertical dependency of $g$: Identical to the global model one.
* Vertical dependency of $N$: The algorithm available in the global model has been extended in the LAM model, but additional issues appear due to the fact that there are two truncations $N_s$ and $N_m$. We still define one reference truncation $N$ for the high stratosphere. We define two vertically varying truncations $N$ and $N_m$ and we consider the following cases:

- **1D model ($N_s = 1$, $N_{ms} = 0$):**
  - $N(l)$ is equal to 1 at all levels.
  - $N_m(l)$ is equal to 0 at all levels.
- **Meridian 2D model ($N_s \geq 1$, $N_{ms} = 0$):**
  - $N(l)$ is computed as in global models from $N_s$ to $N_2$.
  - $N_m(l)$ is equal to 0 at all levels.
- **Zonal 2D model ($N_s = 0$, $N_{ms} \geq 1$):**
  - $N(l)$ is equal to 0 at all levels.
  - $N_m(l)$ is computed as in global models from $N_{ms}$ to $N_2$.
- **Rectangular 3D model with $N_s > N_{ms}$:**
  - $N(l)$ is computed as in global models from $N_s$ to $N_2$.
  - $N_m(l)$ is equal to $\text{nint}((N_{ms}/N_s) * N(l))$.
- **Rectangular 3D model with $N_s < N_{ms}$:**
  - $N_m(l)$ is computed as in global models from $N_{ms}$ to $N_2$.
  - $N(l)$ is equal to $\text{nint}((N_s/N_{ms}) * N_m(l))$.
- **Square 3D model with $N_s = N_{ms}$:**
  - $N(l)$ is computed as in global models from $N_s$ to $N_2$.
  - $N_m(l)$ is equal to $N(l)$.

3.1.3 Main horizontal diffusion scheme in stretched ARPEGE/IFS.

* Expression of mapping factor in spectral space. Let us denote by:
  
  - $a_c = 0.5 \left( c + \frac{3}{2} \right)$
  - $b_c = 0.5 \left( c - \frac{1}{2} \right)$
  - $\epsilon(0,0) = 0$
  - $\epsilon(m,n) = \sqrt{\frac{n^2 - m^2}{2n^2 - 1}}$

Expression of $M$ is:

$$M = a_c + b_c \mu$$

where $\mu$ is the sinus of computational sphere latitude. Expression of $[MX]_{m,n}$ is:

$$[MX]_{m,n} = b_c \epsilon(m,n) X_{(m,n-1)} + a_c X_{(m,n)} + b_c \epsilon(m,n+1) X_{(m,n+1)}$$

A multiplication by $M$ in spectral space is equivalent to a multiplication by a symmetric tridiagonal matrix.

* Discretisation: Calculations are done in spectral space. The discretised equation which is coded is:

$$X_{(m,n)}^- = + b_c \epsilon(m,n) \Omega h_X g(l) Dtf(n-1, N, n_0(X), x_0, r) X_{(m,n-1)}^+$$

$$+ (1 + a_c \Omega h_X g(l) Dtf(n, N, n_0(X), x_0, r)) X_{(m,n)}^+$$

$$+ b_c \epsilon(m,n+1) \Omega h_X g(l) Dtf(n + 1, N, n_0(X), x_0, r) X_{(m,n+1)}^+$$

Equation (24) is equivalent to invert a tridiagonal matrix for each zonal wave number $m$. The computation of this matrix and a decomposition into a product of two triangular bidiagonal matrices are performed in the set-up routine SUHDU. At each time step these two triangular bidiagonal matrices are inverted in order to compute the $X_{(m,n)}^+$. 

8
3.2 Modification of the horizontal diffusion scheme if “SLHD” interpolations are done in the semi-Lagrangian scheme.

* Modified expression of \( g(l) \): We now need two vertical profiles \( g(l) \) and \( g_{\text{hds}}(l) \).
  - Expression of \( g_{\text{hds}}(l) \) has the same shape as \( g(l) \) according to YRDYN\%NPROFILEHD, but \( y_0 \) is replaced by \( y_{\text{hds}} \) (we have the possibility to take \( g_{\text{hds}} \) different from \( y_0 \)).
  - Constant \( s_{\text{dred}} \) is subtracted from \( g(l) \): that provides a modified \( g(l) \) (always \( \geq 0 \)).

* Vertical profiles for \( N \): We now need two vertical profiles \( N(l) \) and \( N_{\text{hds}}(l) \). Both refer to the same reference truncation \( N_2 \). In LAM models we also introduce the additional quantity \( N_{m\text{hds}}(l) \).

* Unstretched global model: A double diffusion is applied on vorticity and divergence (and also the vertical divergence variable in the NH model). It writes:

\[
X^{+}_{(m,n)} = \left[ \frac{1}{1 + K_{\text{hds}}(m)Dt} \right] \left[ \frac{1}{1 + K_X(n)Dt} \right] X^{-}_{(m,n)}
\]

(25)

where:

\[
K_{\text{hds}}(m) = \Omega \ g_{\text{hds}}(m) f(n, N_{\text{hds}}, n_0(X), x_0, s)
\]

(26)

* LAM model: A double diffusion is applied on vorticity and divergence (and also the vertical divergence variable in the NH model). It writes:

\[
X^{+}_{(m,n)} = \left[ \frac{1}{1 + K_{\text{hds}}(m)Dt} \right] \left[ \frac{1}{1 + K_X(n)Dt} \right] X^{-}_{(m,n)}
\]

(27)

where:

\[
K_{\text{hds}}(m, n) = \Omega \ g_{\text{hds}}(m) f(m, n, N_{m\text{hds}}, N_{\text{hds}}, n_0(X), x_0, s)
\]

(28)

* Stretched global model: A double diffusion is applied on vorticity and divergence. It writes:

\[
X^{+}_{(m,n)} = +b_c e_{(m,n)} \Omega \ h_X g(l) Dt f(n - 1, N, n_0(X), x_0, r) X^{+\cdot}_{(m,n-1)}
\]

\[
+ (1 + a_c \Omega \ h_X g(l) Dt f(n, N, n_0(X), x_0, r)) X^{+\cdot}_{(m,n)}
\]

\[
+ b_c e_{(m,n+1)} \Omega \ h_X g(l) Dt f(n + 1, N, n_0(X), x_0, r) X^{+\cdot}_{(m,n+1)}
\]

(29)

then:

\[
X^{+\cdot}_{(m,n)} = +b_c e_{(m,n)} \Omega \ h_{\text{hds}}(l) g_{\text{hds}}(l) Dt f(n - 1, N_{\text{hds}}, n_0(X), x_0, s) X^{+\cdot}_{(m,n-1)}
\]

\[
+ (1 + a_c \Omega \ h_{\text{hds}}(l) g_{\text{hds}}(l) Dt f(n, N_{\text{hds}}, n_0(X), x_0, s)) X^{+\cdot}_{(m,n)}
\]

\[
+ b_c e_{(m,n+1)} \Omega \ h_{\text{hds}}(l) g_{\text{hds}}(l) Dt f(n + 1, N_{\text{hds}}, n_0(X), x_0, s) X^{+\cdot}_{(m,n+1)}
\]

(30)

This discretisation requires to invert two tridiagonal symmetric matrices in spectral space.

3.3 Application of diffusion to each variable.

3.3.1 Application to GMV variables and to GFL variables in 3D models.

For GMV variables, horizontal diffusion is applied to:

- “reduced” vorticity \( \zeta \) with \( n_0(\zeta) = 2 \) at METEO-FRANCE, 0 at ECMWF.
- “reduced” divergence \( D \) with \( n_0(D) = 0 \).
- for temperature, a variable which looks like \( T - \alpha \log(\text{IL}) \) (see part 3.3.2), with \( n_0(T) = 0 \).

* in the NH model, the two additional NH variables, with \( n_0 = 0 \) (and also the auxiliary variable NHX if NVDVAR=4).

About NH variables, some recommendations must be taken into account.

- Vertical divergence and horizontal divergence (and NHX if NVDVAR=4) must be diffused with the same intensity.
It is recommended to diffuse pressure departure too.

- \( \log(\Pi_s) \) should not be diffused (even if some diffusion code is implemented for this variable).

For GFL variables, horizontal diffusion is applied to:

- specific humidity \( q \) if spectral one, with \( n_0(q) = 0 \).
- ozone \( O_3 \) if spectral one, with \( n_0(O_3) = 0 \).
- extra GFL variables if spectral ones, with \( n_0 = 0 \).
- For the other advectable GFL variables and for the non-advectable GFL variables, no diffusion is currently coded.

### 3.3.2 Application to temperature.

Diffusion has to be done on a variable less sensitive to the orography than \( T \), so one chooses a variable looking like \( T - \alpha \log(\Pi_s) \). \( T - \alpha \log(\Pi_s) \) is diffused instead of \( T \), where \( \alpha \) is a coefficient depending on the altitude and using parameters related to standard atmosphere. Let us denote by \( T_{st} \) the surface temperature in a standard atmosphere (288.15 K), \( R \) the air constant, \( G \) the acceleration due to gravity, \( \frac{dT}{dz}_{st} \) the tropospheric temperature vertical gradient in a standard atmosphere (-0.0065 K/m), \( T_{t\, st} \) the tropopause temperature in a standard atmosphere (217.15 K), and \( \Pi_{ref} \) a reference temperature equal to 1013.25 hPa. If:

\[
\left( T_{st} \right) (\Pi/\Pi_{ref}) \left( R/G \right) \left[ \frac{dT}{dz}_{st} \right] > \left( T_{t\, st} \right)
\]

the expression of \( \alpha_l \) for the layer number \( l \) is:

\[
\alpha_l = -B_l \left( R/G \right) \left[ \frac{dT}{dz}_{st} \right] \left( T_{st} \right) (\Pi/\Pi_{ref}) - (\left( R/G \right) \left[ \frac{dT}{dz}_{st} \right] + 1)
\]  

where \( B_l \) is used in the definition of pressure on layers and interlayers (hybrid vertical coordinate). In the other cases:

\[
\alpha_l = 0
\]

Temperature horizontal diffusion writes as:

\[
(T_{\mathbf{+}}(m,n) - \alpha \log(\Pi_s)_{(m,n)}) = \frac{1}{1 + K_T(n)Dt} (T_{\mathbf{-}}(m,n) - \alpha \log(\Pi_s)_{(m,n)})
\]  

Equation (33) yields (34):

\[
T_{\mathbf{+}}(m,n) = (T_{\mathbf{-}}(m,n) + K_T(n)Dt\alpha \log(\Pi_s)_{(m,n)})/(1 + K_T(n)Dt)
\]

For temperature \( n_0(T) = 0 \).

### 3.3.3 Application to GMV variables in 2D models.

Horizontal diffusion is performed for vorticity, divergence and equivalent height.

### 3.4 Other diffusive processes schemes.

#### 3.4.1 Sponge.

We focus on the new sponge done in spectral space for GMV and spectral GFL, and in grid-point space for grid-point GFL variables.

Discretisation of equation (8) is equivalent to write:

\[
X^+ - X_{\text{moy}} = (1 - K_{\text{sponge}}(m,n)Dt)(X^- - X_{\text{moy}})
\]

Coefficient \( K_{\text{sponge}} \) is only vertically-dependent.

In spectral space this is equivalent to write

\[
X^+_{(m=0,n=0)} = X^-_{(m=0,n=0)}
\]

\[
X^+_{(m,n)} = (1 - K_{\text{sponge}}(m,n)Dt)X^-_{(m,n)}
\]

We denote by \( R_{\text{sponge}} \) the quantity \( (1 - K_{\text{sponge}}(m,n)Dt) \). Coefficient \( R_{\text{sponge}} \) depends on variable \( X \), but with the following limitations: there is one coefficient for GMV, one coefficient for spectral GFL and one coefficient for grid-point GFL.

Two heights \( R_{\text{sponge-L}} \) and \( R_{\text{sponge-P}} \) are defined \( R_{\text{sponge-L}} < R_{\text{sponge-P}} \). The minimum value of \( R_{\text{sponge}} \) at the top is \( R_{\text{sponge-L}} \). There is an additional quantity \( R_{\text{sponge-ax}} \) introduced to control the shape of the function defining \( R_{\text{sponge}} \).
• For a standard atmosphere height $z$ lower than $R_{sponbtX}$, $R_{spngX} = 1$.
• For a standard atmosphere height $z$ bigger than $R_{sponptX}$, $R_{spngX} = R_{spngnX}$.
• For a standard atmosphere height $z$ between $R_{sponbtX}$ and $R_{sponptX}$:
$$R_{spngX} = R_{spngnX} + (1 - R_{spngnX})R_{spontauX}T + R_{spontauX}T$$
where $T = \tan(0.5\pi(R_{sponptX} - z)/(R_{sponptX} - R_{sponbtX}))$

For grid-point GFL variables, $X_{moY}$ is always set to 0.

### 3.4.2 Rayleigh friction.

The following scheme is discretised in grid-point space for the $U$-component (and optionally for the $V$-component) of the momentum equation. $LRFRIC=T$, $NAMDYn$ activates Rayleigh friction on $U$; $LRFRICISOTR=T$, $NAMDYn$ activates additional Rayleigh friction on $V$. Rayleigh friction can be done in Fourier space instead of grid-point space if $LEGWWMS=T$ (option used at ECMWF, available in unstretched unshifted global model, and out of the scope of this documentation).

We now focus on calculation of coefficient $K_{fric}$ which appears in equation (9). $K_{fric}$ is a vertically dependent coefficient which is non-zero only for a standard pressure lower than $\Pi_{fric}$ ($\Pi_{fric}$ is stored in variable $YRDYN%RRFPLM$ in YOMDYn). $K_{fric}$ is computed in SURAYFRIC according the following formula:

• If $\Pi_{st}(l) \leq \Pi_{fric}$:
$$K_{fric}(l) = 1 - \frac{1}{7}\tanh\left(\frac{R_{ftau} - 7\log(100000/\Pi_{st}(l))}{R_{ftau}}\right)$$

• If $\Pi_{st}(l) > \Pi_{fric}$: $K_{fric}(l) = 0$

Formula (35) involves the following quantities:

• $R_{ftau}$ is stored in variable $YRDYN%RRFZ1$ in YOMDYn (it controls the inflexion point of the vertical profile).
• $R_{ftau}$ is stored in variable $YRDYN%RRFTAU$ in YOMDYn (it controls the intensity of diffusion).
• $K_{fric}$ is stored in variable $YRDYN%RKRF$ in YOMDYn.

### 3.4.3 Filtering pressure gradient term.

This filtering is activated when $LGRADSP=T$. Spectral filtering is done in routine SPFILT (global models) and ESPFILT (LAM models). It is applied to vorticity component of pressure gradient term. Divergent component is kept unfiltered. In NH LAM models pressure departure is filtered too.

In global models, filter only depends on total wavenumber $n$; no filter is applied for $n + i \leq \lfloor(2/3)N_s - 1\rfloor$, where $i = 0.83N_s$ for $n + i > \lfloor(2/3)N_s - 1\rfloor$ vorticity component is multiplied by a factor $1/(1 + fac^2)$ where $fac = 32\exp(-0.5 \ast (n + i - N_s)^2/(n + i - \lfloor(2/3)N_s - 1\rfloor)^2)$.

A specific formulation is used in LAM models.
4 Organigramme of the horizontal diffusion computations.

4.1 Order of spectral computations.

* Global model: Spectral computations are done in the 3D model in the following order:
  - Mass corrector computations (SPCMASCOR).
  - Semi-implicit computations in the hydrostatic model (SPCSI).
  - Semi-implicit computations in the NH model (SPNHSI).
  - Filtering of pressure gradient term (SPFILT).
  - Main horizontal diffusion scheme and sponge (SPCHOR).
  - Nudging (i.e. linear relaxation towards a pre-defined state) (SPCHOR).

In the 2D model the semi-implicit computations and the main horizontal diffusion scheme are done in SPC2.

* LAM model: Spectral computations are done in the 3D model in the following order:
  - Semi-implicit computations in the hydrostatic model (ESPCSI).
  - Semi-implicit computations in the NH model (ESPNHSI).
  - Spectral nudging (coupling) from a coarser model (ESPSC2R for temporal interpolation providing coupler at the current timestep, ESPCPL for spectral relaxation).
  - Filtering of pressure gradient term (ESPFILT).
  - Main horizontal diffusion scheme and sponge (ESPCHOR).

* Case of iterative centred-implicit schemes: For LPC_FULL, horizontal diffusion can be called at the last iteration or at all iterations of the iterative algorithm according to the value of variable YRDYN\%LRHDI\_LASTITERPC.

4.2 Set-up and control routines until STEPO.

CNT0 ->
  * SUOYOMA ->
    - SUCTO
    - SUDYN
    - SUGEOMETRY
  * SUOYOMB ->
    - SUDYN ->
      * SUALDYN
      * SUALDYNB or SUELDYNB
      * SUHDIR
      * SUHDF or SUHDF\_EC (global model),
        SUHDF2 (2D global model) or SUEHDF (LAM model) [Main diffusion scheme only]
      * SUHDU -> SUHER [Main diffusion scheme in stretched global model only]
      * SURCORDI or SURCORDI\_TH
      * SURAYFRIC
    - SUSPNG
  * CNT1 -> CNT2 -> CNT3 -> CNT4 ->
    - SUHDU -> SUHER [Main diffusion scheme in stretched global model only]
    - STEPO -> (organigramme not detailed)

* Adjoint code: For adjoint code STEPO is replaced by STEPOAD, organigramme is slightly different between CNT0 and STEPOAD. For example CNT3 is replaced by CNT3AD. CNT4 is replaced by CNT4AD.

* Tangent linear code: For tangent linear code STEPO is replaced by STEPOTL, organigramme is slightly different between CNT0 and STEPOTL. For example CNT3 is replaced by CNT3TL. CNT4 is replaced by CNT4TL.

* DFI initialisation: The sequence SUHDU -> SUHER is also called by DFI3 (digital filtering initialisation).
4.3 Direct code under STEPO or tangent linear code under STEPOTL for spectral calculations.

STEPO or STEPOTL →
- SPCM (global model only) →
  - TRMTOS (transposition routine for distributed memory).
  - SPCMSCOR (mass corrector).
  - SPCSII (semi-implicit scheme in the hydrostatic model).
  - SPNHHSII (semi-implicit scheme in the NH model).
  - TRSTOM (transposition routine for distributed memory).
  - SPFILT (pressure gradient term filtering).
  - SPCIIOR → MXTURHD (horizontal diffusion, sponge and nudging).

- ESPCM (LAM model only) →
  - TRMTOS (transposition routine for distributed memory).
  - ESPCII (semi-implicit scheme in the hydrostatic model).
  - ESPNHHSII (semi-implicit scheme in the NH model).
  - ESPC2R and ESPCPL (spectral nudging (coupling) from a coarser model).
  - ESPFILT (pressure gradient term filtering).
  - ESPCIOR → MXTURHD (horizontal diffusion, sponge).
  - TRSTOM (transposition routine for distributed memory).

- SPC2M (global model only) → SPC2 →
  - MXTURS
  - MXTURE
  - MXPTMA
  - BALADSM

- GPNSPNG (sponge for grid-point GFL variables).

4.4 Adjoint code under STEPOAD for spectral calculations.

STEPOAD →
- SPCMAD (global model only) →
  - BRPTOB (communication routine for distributed memory) → PE2SET
  - SPCIIORAD → MXTURHD and GATHERT (horizontal diffusion).
  - TRMTOS (transposition routine for distributed memory).
  - SPCCIAD (semi-implicit scheme for the hydrostatic model).
  - SPNHSIAD (semi-implicit scheme for the NH model).
  - TRSTOM (transposition routine for distributed memory)

- ESPCMAD (LAM model only) →
  - TRMTOS (transposition routine for distributed memory).
  - ESPCIIORAD → MXTURHD and GATHERT (horizontal diffusion).
  - ESPCIIAD (semi-implicit scheme for the hydrostatic model).
  - TRSTOM (transposition routine for distributed memory).

- SPC2MAD (ARPEGE/IFS only) → SPC2AD →
  - MXTURS
  - MXTURE
  - MXPTMA

4.5 Rayleigh friction done in grid-point space.

Rayleigh friction is done in the grid-point calculations under CPG_GP -> GP_TNDLAGADIAB_UV if LEGWWMS=F. There is some Rayleigh diffusion code (done in Fourier space) under the sequence

LTINV -> ASRE1 -> ASRE1B -> FSPGL_INT -> adiab/FSPGLH

activated only if LEGWWMS=T.
4.6 Action done by set-up routines.

- **SUCT0**: computes 0-level control variables.
- **SUGEOMETRY**: computes geometry object variables.
- **SUALDYN, SUALDYNB, SUELDYNB**: allocates some arrays used in the dynamics, in particular those used in the horizontal diffusion.
- **SUDYNA**: computes some variables used in the dynamics; for example **LGRADSP**.
- **SUDYN**: caller for the following ones:
  - **SUHDIR**: computes the coefficients **HDIR**, **HRDIR**, **RDAMP**.
  - **SUHDF**: computes the arrays **RDI**, **RDS**.
  - **SUHDF_EC**: version of **SUHDF** used at ECMWF.
  - **SUHDF2**: cf. **SUHDF** but for 2D models.
  - **SUEHDF**: for LAM model; computes the arrays **RDI**...**E**, **RDS**...**E**.
  - **SURCORDI**: computes the array **RCORDIT**.
  - **SURAYFRIC**: computes the setup of the Rayleigh friction.
  - **SUHDU**: fills **RDHI** of **YOMDYN**. Array **RDHI** contains the non-zero diagonals of the two triangular bidiagonal matrices, the product of which defines the inverse of horizontal diffusion operator (right-hand side member of equation (24)).
- **SUSPNG** (encapsulated in module **SPNG_MOD**): computes the setup of the sponge.

4.7 Control routines.

- **CNT0**, **CNT1**, **CNT2**, **CNT3**, **CNT4**, **CNT3AD**, **CNT4AD**, **CNT3TL**, **CNT4TL**, **STEPO**, **STEPOAD**, **STEPOTL** are control routines. **STEPO** (resp. **STEPOAD**, **STEPOTL**) manages one direct (resp. adjoint, tangent linear) integration timestep.

4.8 Action done by routines under **STEPO**, **STEPOAD** or **STEPOTL**.

**Algorithmic routines:**

- **SPCHOR**: spectral horizontal diffusion schemes (except Rayleigh friction) and nudging in the 3D model.
- **SPFILT**: filtering of pressure gradient term in spectral space.
- **SPC2**: spectral space computations, including the semi-implicit scheme and all horizontal diffusion schemes in the 2D model.
- **SPCM**: interface routine for **SPCHOR**.
- **SPC2M**: interface routine for **SPC2**.
- **ESPCM**, **ESPC2M**, **ESPCHOR**, **ESPC2** are called instead of **SPCM**, **SPC2M**, **SPCHOR**, **SPC2** in LAM model.

These routines have adjoints (same names + “AD”). Horizontal diffusion on post-processed fields and nudging are not yet coded in **SPCHORAD**.

- **BALADSM**: solve linear balance equation in spectral space to convert vorticity into geopotential (used for vorticity 2D equation only).

**Linear algebra routines (project “algor”):**

- **MXTURE**: called by **SPC2** and inverts bidiagonal or tridiagonal triangular linear systems.
- **MXTURHD** is a version of **MXTURE** well suited for horizontal diffusion.
- **MXTURS**: combines two calls to **MXTURE** to invert a set of symmetric tridiagonal or pentadiagonal matrices, the decomposition **LU** of which is known. Called by **SPC2**.
- **MXPTMA**: products of a set of tridiagonal or pentadiagonal matrices by a set of matrices or vectors. Called by **SPC2**.
- **SUHER**: performs the **LU** factorisations of a set of non symmetric tridiagonal matrices.

**Distributed memory routines (for ex. transposition routines) doing communications between processors:** the list of transposition and communication routines used in horizontal diffusion scheme is the following: **TRSTOM**, **TRMTOS**, **BRPTOB**, **MPL_ALLREDUCE**, **GATHERT**, **PE2SET** and **SET2PE**; see documentation (IDDM) about distributed memory features for the action of these routines.
5 Some distributed memory features in spectral space.

- The total number of processors involved in the A-level parallelisation is $N_{PRTRW}$.
- The total number of processors involved in the B-level parallelisation is $N_{PRTRV}$.
- The total number of processors $N_{PROC} = N_{PRTRW} \times N_{PRTRV}$.
- One processor treats only a subset of zonal wave numbers.
- A call to SPCHOR can treat several wave numbers (currently all the zonal wave numbers treated by the current processor). For computations needing matricial operations (geographical component of unified diffusion scheme for example) calculations are split zonal wave number by zonal wave number inside SPCHOR.
- For 2D model a call to SPC2 treats only one zonal wave number.
- For the 3D model there is a splitting into $NFLEVL$ layers packets when $N_{PRTRV} > 1$. One B-set processor treats $NFLEVL$ layers; an exception is done in the adjoint code SPCHORAD when diffusing variables using the temperature array, some calculations on all the $NFLEVG$ layers are necessary to compute a vertical integral which does not exist in the direct code. That means that additional transpositions (TRSTOM in the direct code) are necessary between the semi-implicit calculations of SPCSI and the horizontal diffusion calculations of SPCHOR to convert the fields from the $NFLEVG$ structure required in the semi-implicit calculations to the $NFLEVL$ structure required in the horizontal diffusion calculations.
- LAM model does not completely follow global model for the second level of distribution: the $NFLEVL$ structure is not yet implemented in ESPCHOR, and ESPCHOR works like SPCSI. That explains why the order of calls is SPCSI, TRSTOM, SPCHOR in global model, but ESPCSI, ESPCHOR, TRSTOM in LAM model.
6 Module and namelist variables.

These modules are auto-documented so description of each variable is provided in the code source. We can recall here the most important variables to know for each module:

- **SPGEOM MOD** (spectral geometry).
- **YEMGEO** (LAM model geometry): in particular ELX, ELY, EDELX, EDELY. Some of these variables are in namelist NEMGEO.
- **YOMGEM** (computational space grid-point horizontal geometry). Some of these variables are in namelist NAMGEM.
- **YOMLAP** (Laplace space).
- **YOMVERT** (vertical geometry).

- **SPNG_MOD** (module for new sponge): 
  - LNSPONGE: to switch on new sponge.
  - RSPONBT (RspontX), RSPONTP (Rspontpx), RSPONTAU (RspontauX), RSPONGN (Rspngx), RSPONGF (RspngX).
  
  Some of these variables are in namelist NAMSPNG.

- **YOMARG** (0-level control, former command line) and **YOMCT0** (0-level control):
  - NCONF, LECMWF, LELAM (in NAMARG).
  - LR3D, LR2D, LRSHW, LBVEQ.
  - LRPLANE (in NAMCT0).

- **YOMDIM, YOMDIMV** and **YOMDIMH** (dimensioning): most of variables. Some of these variables are in namelist NAMDIM.

- **YOMDYNA** (adiabatic dynamics: first part):
  - LSLHD (internal model key for SLHD = semi-Lagrangian diffusion computation).
  - LSLHDW, LSLHD_T, LSLHD_SPD, LSLHD_SVD, LSLHD_OLD, LSLHD_STATIC, LSLHDQUAD (keys for SLHD).
  - SLHDKMIN, SLHDKMAX, SLHDEPSH, SLHDEPSV (values used in SLHD).
  
  Some of these variables are in namelist NAMDYNA.

- **YOMDYN** (adiabatic dynamics: second part). All these variables are attributes of YRDYN.

  - Main horizontal diffusion scheme:
    * HDIR[X] (1/(Ωhx)).
    * HRDIR[X] ((Ωhx), i.e. 1/HDIR[X]).
    * FRANDH (x0 in equation (14)).
    * REXPDH (r = order of the horizontal diffusion operator).
    * SLEVDH and SLEVDH3 (thresholds y0 and y3 in formula defining g(l)).
    * SLEVDH1 and SLEVDH2 (thresholds y1 and y2 in formula defining N(l)).
    * NSREFDH (N2).
    * NPROFILEHD (type of vertical profile for function g(l)).
    * RPROFHDBT, RPROFHDT, RPROFHDIMX, RPROFHIDEX (used if NPROFILEHD=2).
    * LRDISPE_EC (controls horizontal function used in the horizontal diffusion).
    * RDIX (contains KX, see equation (13)).
    * RCORDIT (contains K, used in equations (31) and (33)).
    * RRDXTAU (rdtau), RDAMP[X] (rdampX).
    * LSTRHD.
    * RDHI.

  - Additional quantities used if SLHD scheme is activated:
    * HDSR[X] (1/(Ωhdsx)).
    * HRDSRX (Ωhdsx).
    * REXPDHS (s = order of the additional horizontal diffusion operator).
    * SLEVDHS (thresholds yhds in formula defining ghds(l)).
- SLEVDHS1 and SLEVDHS2 (thresholds $y_{hds1}$ and $y_{hds2}$ in formula defining $N_{hds}(l)$).
- RDS[X] (contains $K_{hds-X}$, see equation (26)).
- RDAMPHDS (coefficient $r_{damphds}$).
- RDAMP[X]: cf. RDAMP[X] for additional diffusion.
- SDRED (coefficient $s_{direct}$).
- RDHS (cf. RDHI for additional diffusion).

- Rayleigh friction:
  - LRFRIC and LRFRICISOTR.
  - RKRF ($K_{fric}$), NMAXLEVRF, RRFZ1 ($R_{z1}$), RRFPLM ($\Pi_{fric}$), RRFTAU ($R_{tau}$).

Some of these variables are in namelist NAMdyn.

- **YEMdyn** (LAM model dynamics). All these variables are attributes of YREDYN.
  - RDIVORE, RDIIVOE, RDITE, RDIEGFL, RDISPE, RDIPE, RDIVDE (LAM counterparts of RDIVOR to RDIVD).
  - RDSVORE, RDSDIVF, RDSVDE (LAM counterparts of RDSVOR to RDSVD).
  - REFILV and REFILD (for pressure gradient filtering).

- **YOMGFL** (GFL dataflow, in particular GFL%Y[X]%LSLHD and GFL%Y[X]_NL%LSLHD).
- **YOMMPO** and **YOMMP** (distributed memory environment, see documentation (IDDM) for more details).
- **YOMNUD** (nudging); some of variables are in namelist NAMNUD.
- **YOMSP** and **YOMSP5** (spectral arrays).
- **Spectral_fields_mod** (spectral arrays, in particular type SPECTRAL_FIELD), in project “algor”.
7 References.

7.1 Publications:


7.2 Internal notes:

- (TDECDYN) 2016: IFS technical documentation (CY41R2). Part III: dynamics and numerical procedures. Available at “https://software.ecmwf.int/wiki/display/IFS/Official+IFS+Documentation”.
- (TDECTEC) 2016: IFS technical documentation (CY41R2). Part VI: technical and computational procedures. Available at “https://software.ecmwf.int/wiki/display/IFS/Official+IFS+Documentation”.
- (IDEUL) Yessad, K., 2017: Integration of the model equations, and Eulerian dynamics, in the cycle 45 of ARPEGE/IFS (internal note, available on the intranet server “http://www.umr-cnrm.fr/gmapdoc/”).

18